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## Hot electron tunable supercurrent

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A Josephson junction has been realized in which the supercurrent flow is regulated by a “normal” control current traversing the normal metal in between the superconducting electrodes. The principle of operation of the devices is based on the existing relation between the magnitude of the supercurrent and the electronic distribution function in the junction. This method for controlling the supercurrent has clear advantages over other known methods and is relevant for superconducting electronics applications. © 1998 American Institute of Physics. [S0003-6951(98)01008-0]

The ability to control the supercurrent flow in a superconducting junction has always received considerable attention in the field of applied superconductivity, since it gives access to a variety of possible applications. There exist a number of well known ways in which supercurrent tuning has been achieved in the past.<sup>1</sup> For instance, the use of superconducting junctions coupled via a two dimensional electron gas present in a semiconducting heterostructure permits one to control the supercurrent flow by acting on the electron density in the semiconductor with a gate electrode.<sup>2</sup> Aside from the technological difficulties involved in the fabrication of these devices (which can be realized only with a limited variety of semiconducting materials, and not with metals, between the superconducting electrodes), a serious drawback in their practical applications is the large difference between the voltage required to change the electron density ( $\approx 1\text{--}10$  V) and the characteristic voltage scale associated with superconductivity ( $\approx 1$  mV).

Another way in which the supercurrent flow can be controlled is by suppressing the superconducting gap in one of the junction electrodes, which can be done by injecting into it a sufficiently large current.<sup>3</sup> This method has been thoroughly investigated in relation to the study of superconducting transistors, and it has been shown to have some fundamental limitations. In particular its speed appears to be limited by a transient response on a 1 ns scale, intrinsically related to the on/off switching of the superconducting state.<sup>1,4</sup>

In this letter we propose and demonstrate experimentally a new method to control superconducting flow, whose operation is based on the relation between supercurrent and population of electronic states in the region separating the superconducting electrodes of the junction. This method can be implemented in different kinds of junctions, including entirely metallic junctions and junctions in which the superconducting electrodes are coupled via a semiconductor, without suffering from the limitations mentioned above. The principle of operation does not depend on the properties of the superconducting electrodes and is compatible with the use of high  $T_c$  ceramic superconductors.

In order to discuss the principle of operation of our de-

vices we start with introducing the required theoretical concepts, based on the Bogolubov–de Gennes<sup>5</sup> equations which describe the supercurrent flow (in a generic Josephson junction) in terms of the electronic states present in the region between the superconducting electrodes. Without going into the details extensively discussed in literature,<sup>6</sup> we write the expression for the supercurrent  $I_s$  as a function of the superconducting phase difference  $\phi$  as:

$$I_s(\phi) = I_{bs}(\phi) + I_{cont}(\phi). \quad (1)$$

In this equation  $I_{bs}$  is the contribution to the supercurrent given by discrete bound states whose energy (relative to the Fermi energy  $E_F$  in the electrodes) is smaller than  $\Delta$ , the superconducting energy gap, whereas  $I_{cont}$  is the contribution of the continuum of states at larger energy. The theoretical expression for these two contribution reads:

$$I_{bs}(\phi) = \sum_n I[E_n^+(\phi)]p_n^+ + I[E_n^-(\phi)]p_n^- \quad (2)$$

$$I_{cont}(\phi) = \left( \int_{-\infty}^{-\Delta} + \int_{\Delta}^{\infty} \right) I(E, \phi) p(E, \phi) dE.$$

Here  $E_n^+(\phi)$  [ $E_n^-(\phi)$ ] is the energy of the  $n$ th bound state carrying current in the positive (negative) direction,  $I(E_n^{+(-)})$  is the contribution of these bound states to the supercurrent and  $p_n^{+(-)}$  are their occupation probabilities (which in equilibrium are determined by the Fermi–Dirac distribution). In a similar way,  $I(E, \phi)$  is the net contribution of the continuum states having energy between  $E$  and  $E + dE$ , and  $p(E, \phi)$  is their occupation probability.

The relevant feature of the above expression for the supercurrent, as opposed to several equivalent others, is that it shows explicitly how, in general, the supercurrent depends on the occupation of the electronic states.<sup>7</sup> It follows from this dependence that in any superconducting junction it is possible to control the supercurrent flow by acting on the electronic population.<sup>8</sup> This is the method that we propose and that we are going to demonstrate experimentally.

In practice one has to find a way to influence the electronic population and a suitable kind of junctions to implement it. We have chosen to influence the electronic distribution in a SNS junction by electrical means, using devices like those shown in Fig. 1. Similarly to what happens in a con-

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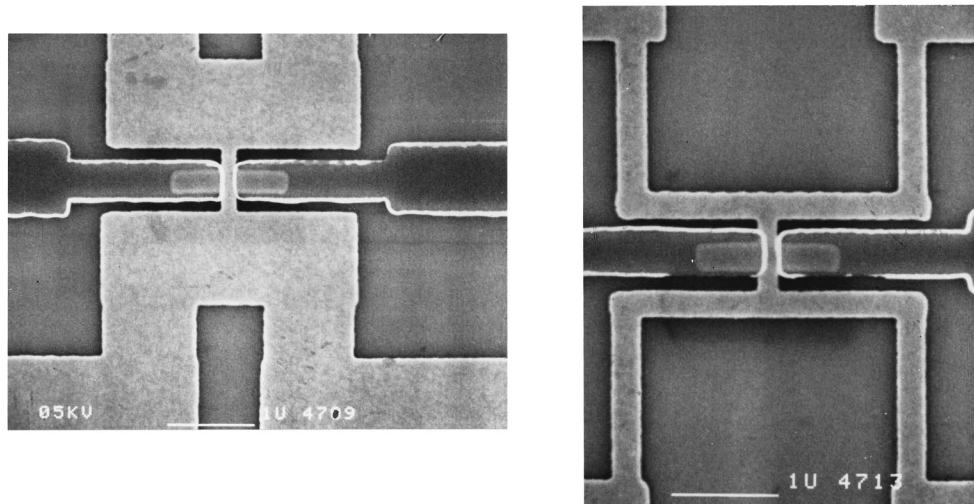


FIG. 1. Two different configurations of devices studied. Two Nb superconducting electrodes (dark horizontal parts in the center of the figures) are connected via an Au film (bright part) which allows us to inject “normal” current through the junction. In both figures the white bar is 1  $\mu\text{m}$  long.

ventional normal metal coupled superconducting weak link, two Nb electrodes are connected via a short Au strip. However, two additional side connections to the Au strip are also present, making it possible to inject “normal” current in the same region traversed by the supercurrent.

We now describe the sample fabrication, referring to the configuration of Fig. 1 (left), which will be discussed more extensively. The samples have been realized on a thermally oxidized Si substrate by means of a two step electron beam lithography process. In the first step the Au pattern is defined by means of electron beam deposition and lift-off (Au thickness  $\approx 40$  nm; Au square resistance  $\approx 0.5 \Omega$ ). In the second step the Nb electrodes are deposited on top of the Au using sputtering and again lift-off. The part of the Au in contact with the Nb electrodes is cleaned by Ar bombardment in a plasma, *in situ*, prior to the Nb deposition, ensuring a high quality electrical contact between the two metals. Devices having two different values for superconducting inter-electrode separation (190 and 370 nm, respectively) have been used. The width of the Au leads used to inject the “normal” current is  $\approx 150$  nm. These leads are connected to Au side contacts and the total length from one side contact to the other is  $\approx 0.7 \mu\text{m}$ . Because the electronic mean free path,  $l_e \approx 40$  nm, is significantly smaller than the geometrical dimensions, the motion of the electrons in the Au is diffusive.

Again with reference to the device of Fig. 1 (left), a typical experiment consists in measuring the current–voltage ( $I$ – $V$ ) characteristic of the junction for different values of the current flowing from one to the other of the Au side contacts (hereafter the path followed by the control current will be referred to as “the control line”). The result of these measurements performed at 1.7 K are shown in Fig. 2. The supercurrent manifests itself in the region of the junction  $I \neq 0$  while the voltage across the superconducting electrodes is  $V = 0$ . It is apparent that the width of this region decreases monotonically with the increase of control current  $I_{\text{control}}$  and that, by injecting a sufficiently large control current, it is possible to completely suppress the critical current of the

junction. This behavior has been observed in all the devices investigated: it directly demonstrates the controllability of the supercurrent by means of a “normal” current flowing through the normal region of a weak link.

It is quite easy to understand qualitatively the origin of the “interaction” between the control current and the supercurrent. Because of the finite voltage difference present across the control line, the control current is carried by electrons which, on average, have larger energy than those present at equilibrium in the weak link. This excess of high energy or “hot” electrons modifies the electronic distribution in the weak link and tends to equilibrate the occupation of bound states carrying current in opposite directions and, as a consequence, the magnitude of the supercurrent is suppressed.<sup>8</sup>

A more precise analysis requires the knowledge of the shape of the nonequilibrium distribution induced by the control current. In this respect it is important to note that, in our experiment, the electrons injected in the control line from one of the side contacts have a rather low probability to scatter inelastically with phonons before reaching the opposite contact. In fact the electron–phonon scattering time in Au at 4.2 K is  $\approx 1$  ns and during this time an electron is able

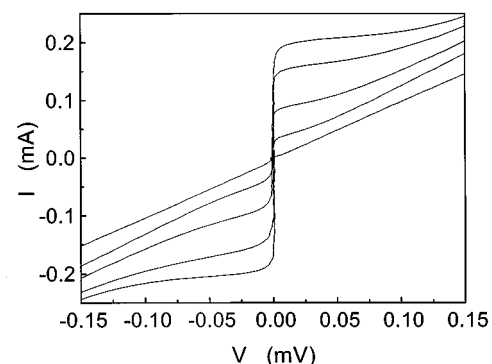


FIG. 2.  $I$ – $V$  curves of the device shown in Fig. 1 (left), for different values of the current through the control line ( $I_{\text{control}}$  equal to 0, 90, 180, 280, 440  $\mu\text{A}$ ): it is evident that the critical current is entirely suppressed by the largest current.

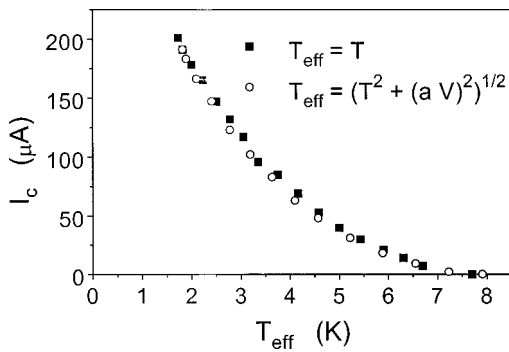


FIG. 3. Critical current as a function of physical temperature (filled squares) and of the effective temperature  $T_{\text{eff}}$  (empty circles).

to diffuse for several microns, a distance significantly larger than the control line length.

In this transport regime and if we assume that electron-electron interaction is strong enough to bring the electrons into equilibrium among themselves, the electron population is described by a Fermi-Dirac distribution with an effective temperature  $T_{\text{eff}} = \sqrt{T^2 + (aV)^2}$  (where  $T$  is the physical temperature and  $a$  is a constant whose value, in the center of the control line, is equal to 3.2 K/mV).<sup>9</sup> We expect that for electrons at energy smaller than  $\Delta$  this conclusion is not substantially influenced by the presence of the superconducting electrodes, since electrons cannot leak out into the electrodes and no heat can flow through an NS interface at that energy.<sup>10</sup> In Fig. 3 the dependence of the critical current on  $T_{\text{eff}}$  is compared with its dependence on the physical temperature  $T$ : the two curves fall essentially on top of each other if, however,<sup>11</sup>  $a \approx 6$  K/mV.

We want to emphasize that it is the nonequilibrium of the electronic distribution, and not the fact that a “normal” current actually flows through the junction, that is relevant in controlling the supercurrent flow. We have verified this result experimentally, using the samples shown in Fig. 1 (right), in which we can force a “normal” current through one of the Au side lines parallel to the junction. In that case no net current flows through the Au between the Nb electrodes, however the electronic distribution is modified by “hot electrons” diffusing from the Au side line, which also are allowed in this configuration to completely suppress the supercurrent flow.<sup>12</sup>

We now proceed to comment on the relevance of the effect for applications.<sup>13</sup> In this respect we first note that in the experiments discussed so far we have always used (for simplicity) the samples as four terminal devices. It is of course possible to tune the supercurrent by injecting the control current from one of the side Au contacts into one of the superconducting electrodes, thus obtaining a three terminal device.

Independently of the specific application, the speed of these devices is related to the time that it takes to create a nonequilibrium electron distribution in the junction, by means of electron diffusion, equal to<sup>14</sup>  $L^2/D$ , where  $L$  is the control line length and  $D$  the Au diffusion constant. In the device shown in Fig. 1 (left), this time is  $2 \times 10^{-11}$  s. This time is not fundamentally limited: it can be made smaller by reducing the sample size (for which purpose a vertical device configuration can be advantageous over the planar one, con-

sidered here). A further decrease in switching time can be achieved by using a junction in which the two superconductors are coupled via a ballistic two dimensional electron gas.

We also note that the voltage across the control line (i.e., the device input) is comparable to that between the superconducting electrodes (i.e., the device output). In fact, we have observed for the device in Fig. 1 (left) a small signal voltage gain in the appropriate bias conditions, at 1.7 K. The gain can be improved by a better sample design, for instance by inserting tunnel barriers of optimal transparency between the Au and the Nb to increase the junction  $R_N I_c$  product.<sup>15</sup>

The considerations just made indicate the concrete possibility of using the hot electron tunable supercurrent principle to realize superconducting transistors performing better than those realized in the past. Apart from possible general use, which cannot be seriously predicted at this stage, these transistors can be useful in research applications at dilution refrigerator temperature. In addition, more specific applications of our devices are possible. A few examples are very fast bolometer mixers<sup>14</sup> with a large intermediate frequency bandwidth and any superconducting quantum interference device (SQUID) application where one would like the two junctions in the SQUID to have variable (e.g., finely tunable or modulable at high frequency) supercurrents.

<sup>1</sup>A. W. Kleinsasser and W. J. Gallagher, in *Superconducting Devices*, edited by Ruggiero-Rudman (Academic, New York, 1990).

<sup>2</sup>T. Akazaki, H. Takayanagi, J. Nitta, and T. Enoki, Appl. Phys. Lett. **68**, 418 (1996).

<sup>3</sup>S. M. Faris, U. S. patent No. 4334158 (1980).

<sup>4</sup>M. Tinkham, *Introduction to Superconductivity*, 2nd ed. (McGraw-Hill, New York, 1996).

<sup>5</sup>P. G. de Gennes, *Superconductivity of Metals and Alloys* (Benjamin, New York, 1966).

<sup>6</sup>See, e.g., C. W. J. Beenakker, Phys. Rev. Lett. **67**, 3836 (1991); P. F. Bagwell, Phys. Rev. B **46**, 12573 (1992).

<sup>7</sup>B. J. van Wees, K. M. H. Lenssen, and C. J. P. M. Harmans, Phys. Rev. B **44**, 470 (1991); G. Wendin and V. S. Shumeiko, *ibid.* **53**, 6006 (1996).

<sup>8</sup>It is important to realize that the states  $E_n^+$  and  $E_n^-$  contribute to the supercurrent with opposite sign (i.e., electrons in those states carry supercurrent in opposite directions). If one populates the + and - states with equal probability, the total supercurrent in the junction vanishes.

<sup>9</sup>H. Pothier, S. Gueron, N. O. Birge, D. Esteve, and M. H. Devoret, Z. Phys. B **104**, 178 (1997), and references therein.

<sup>10</sup>A. F. Andreev, Zh. Eksp. Teor. Fiz. **46**, 1823 (1964) [Sov. Phys. JETP **19**, 1228 (1964)].

<sup>11</sup>This discrepancy may be due to the fact that, in our devices, the normal contacts connected to the control line are not in perfect equilibrium when the control current flows, contrary to what is theoretically assumed in the derivation of the expression for  $T_{\text{eff}}$ .

<sup>12</sup>It is worth pointing out that, whereas in our experiments the control current always increases the average energy of the electrons in the junction ( $T_{\text{eff}} > T$ ), leading to a decrease in the supercurrent, one can design suitable junctions and control lines in which the opposite effect is achieved. In such a system an increase in the control current results in a reduction of the average electron energy, thus effectively “cooling” [see, e.g., M. M. Leivo, J. P. Pekola, and D. V. Averin, Appl. Phys. Lett. **68**, 1996 (1996)] the electrons and enhancing the supercurrent.

<sup>13</sup>A. F. Morpurgo and T. M. Klapwijk (patent pending).

<sup>14</sup>D. Prober, Appl. Phys. Lett. **62**, 2119 (1993).

<sup>15</sup>In our junctions the  $R_N I_c$  product is consistent with what we expect for diffusive SNS superconducting junctions with transparent interfaces [F. K. Wilhelm, A. D. Zaikin, and G. Scön, Czech. J. Phys. **46**, 2394 (1996)].